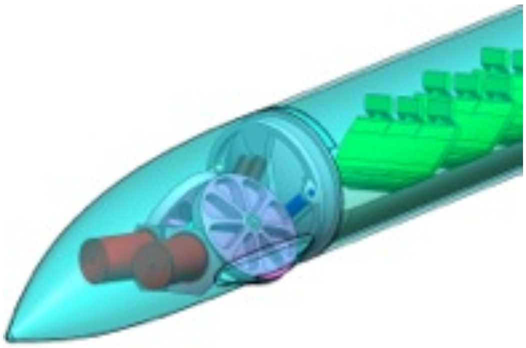
Hyperloop is now more achievable with the Cheetah development

Richard Macfarlane. January 2014

Hyperloop Cheetah is a development of Elon Musk's brilliant Hyperloop Alpha proposal. The technology has evolved, using Alpha as a broad foundation rather than being constrained by every design choice.

Cheetah - sleek, fast and very smart

Cheetah now has quite simple technology, making the Hyperloop project very achievable, and a competitive alternative to high-speed rail projects.



Wheels instead of the air bearing skis.

Wheels offer a practical and achievable solution to suspension, traction, braking and steering. They have been successfully used at Hyperloop speeds, and they satisfy all the calculations for grip, centrifugal and gyroscopic forces, wear and stability.

Kantrowitz Limit solved.

The movement of the pod in the tube creates a back-flow between the pod and tube. This flow speed cannot exceed the speed of sound, so the solution is to compress the gas to increase its density and achieve the required mass flow rate. Alpha does this by compressing the air about 20:1 to pass most of the air displaced by the pod through a duct in the pod.

Cheetah does not use a compressor. The tube contains steam (water vapour) which has a higher speed of sound, reducing the nominal Mach number from 0.96 to 0.76, partially solving the problem.

The thrust from the wheels moves the pod, working like a piston, it increases the pressure, density and the mass flow through the gap between the pod and tube. The pressure ratio is about 2.4:1, requiring just 53kW of power, much less than Alpha's compressor power.

Cooling using steam, ejected then pumped to condensers.

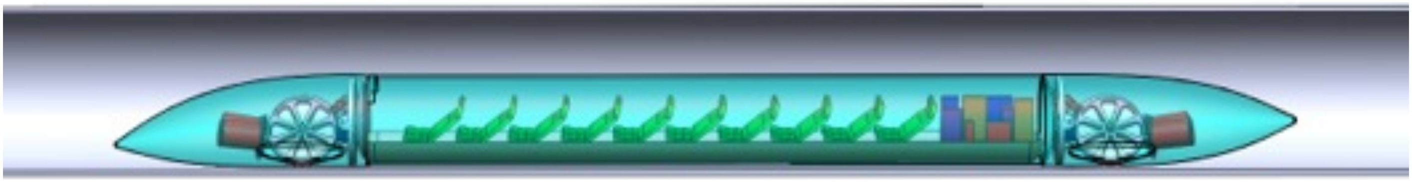
Cooling was recognised by Alpha as a serous problem. The passengers, electrical and mechanical parts must be kept cool, and the near-vacuum has very little capacity to store or conduct heat. It is equivalent to having a 300 kW heater in a normal sized room. Alpha proposed evaporating water to steam to absorb the heat, but had a problem with storing the large volume of steam.

Cheetah has the same cooling system, but ejects the steam into the tube. Along the tube will be compressors to pump the steam out to condensers. The power for this is about 100 kW per pod, it is economical because the condenser pressure is much lower than atmospheric.

Traction using wheels instead of linear motors.

Cheetah uses the wheels for traction and regenerative braking, with a maximum acceleration of 0.3g and power of 3,500 kW. This is less than Alpha, which initially adds 2 minutes, but the actual trip time is reduced by being able to accelerate between every corner.

Alpha uses 6 short lengths of linear motors to give 1g acceleration, using a peak power of nearly 30,000 kW, supplied by batteries outside the tube.



Hyperloop Cheetah Specifications

- Maximum speed 1,220 km/h (760 mph). LA-SF trip time 35 mins approx.
- Pressure hull size, 1.6 M (63”) internal diameter, length 13 M. Pod length 22 M (72ft)
- Pod external dia 1.7 M. Tube internal dia 2.5 M (8ft 3”). Tube/pod area ratio = 2.16
- Construction - monocoque using carbon/epoxy/honeycomb pressure hull.
- Weight 5,000 Kg empty, 9,000 kg (19,800 lb) loaded.
- 30 Passengers, 10 rows of 3 economy or 2 business. Seating module rolls out at station.
- Full-size airlock door on front, plus 2 emergency exits and temporary aisle between seats.
- 4 wheels, 1,300 mm diameter x 150 mm wide (51”x 6”). 4,900 rpm.
- Wheels, forged aluminium alloy, or carbon/epoxy with a hard steel rim.
- 4 electric motors, 900 kW peak power.
- Acceleration, 0.25g up to 430 km/h, then limited by 3,500 kW power, 0.12g at full speed
- Cooling water for trip 250 Kg, steam ejected to tube and compressed to condensers.

Energy Consumption is just 4% of other transport

The estimated full-speed cruising energy consumption for the pod is 140 kW, this increases to 352 kW when including braking losses, cooling power and motor efficiency.

The energy used per passenger per unit distance (40 kJ or 11 Whr per Passenger-km) is about 4% of other forms of public transport.

Compared to the Tesla Model S, which is extremely efficient transport, Hyperloop Cheetah uses 33% more energy per trip, but carries 30 passengers.

Tube absolute pressure Pa	100
Tube inside diameter M	2.500
Power consumption kW	
Wheel & bearings rolling power	58.9
Kantrowitz Compression power	53.2
Skin friction power	28.5
Avge power loss for braking	71.4
Motor and gearbox power loss	37.4
Cooling steam pumping power	103.3
Total Electrical Power kW	**352.6**

Kantrowitz Limit

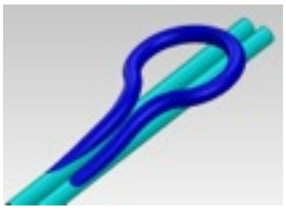
This limits the gas flow thorough a pipe or nozzle to the speed of sound. With suction, where the inlet pressure and density is fixed, the flow is limited regardless of the suction behind. With compression, the gas speed is limited, but we can get any mass flow we require by increasing the inlet pressure and density.

The pod in the tube displaces gas which needs to pass through the annulus between the pod and tube. At about 700 km/h (435 mph) for Alpha in air, and 1000 km/h (620 mph) for Cheetah in steam, the gas speed reaches the speed of sound, and will go no faster. We can only increase speed by compressing the gas and increasing its density.

Alpha compresses part of the air through a small duct, the velocity is limited by Kantrowitz, but with a compression ratio of about 30, the required mass flow of high-density air is achieved.

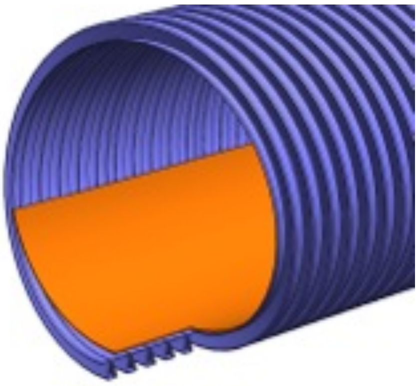
Another way to do it would be a tube-sized propellor on the nose, the pressure needs to be increased about 150% to get the mass flow. In a near-vacuum the pressures are low, and the power to do this is much less than the several hundred kW used by Alpha. The bigger the 'duct', the lower the pressure ratio and the power used.

Cheetah does it it by forcing the pod along the tube using the thrust of wheels. The pressure of the gas in front will build up until the higher pressure increases the density and allows the required mass to flow. This is the simplest solution, and low-energy because a linear 'pump' is more efficient. The drag from building up the pressure is about 16 kgf, and 53 kW of power.



The other benefit of thrust-induced pressure is that part of the gas is forced down the tube if the ends of the tube are linked. This allows the pods to generate their own tailwind, a power saving up to 20% when the system is busy.

The Tube



The accuracy of the tube is important, whichever suspension system is used. Limited accuracy is possible with a fabricated steel tube, and machining would be necessary to give a good surface to avoid bouncing and wear. A good option is to fabricate the tube with reasonable accuracy, then cast hard polyurethane into it using a very precise internal mould.

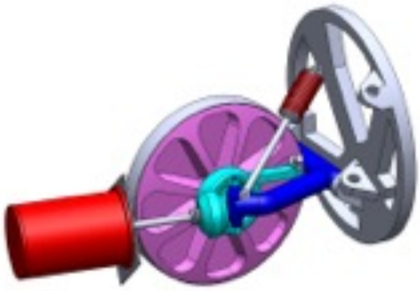
The diagram shows a very economical spiral wound convoluted tube, with a cast PU liner. The PU would give better grip for the wheels, less wear, and a smoother and quieter ride. The considerable extra cost of the PU liner would be offset by the lower steel and fabrication costs.

Wheels

Wheels at this speed are challenging, but we have the advantage of experience to analyse the issues and work out the solutions. All the stresses and issues have been carefully analysed, and a forged aluminium or carbon-epoxy wheel with a hard steel rim would be suitable.

It is encouraging that wheels have already been tested at Hyperloop speeds. Andy Green achieved 1,227 km/h (763mph) using forged alloy wheels, and is building Bloodhound to do 1,600 km/h with similar wheels. But we are not as brave as Andy, and need to do our own calculations.

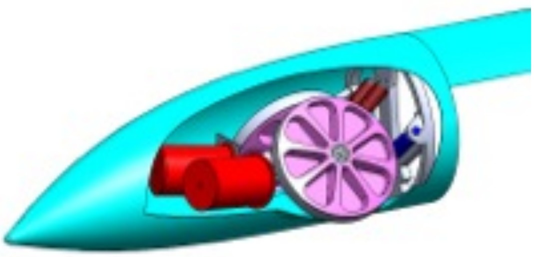
Aluminium wheels will run at 1,600 kph on Bloodhound



They would be 1.3m diameter, 150mm wide (51"x 6"), and angled in the tube. The tube would be bare steel, or possibly a hard polyurethane liner.

The usable friction coefficient would be about 0.35 for metal-on-metal, and greater for metal-on-PU. This grip will give good performance, see the section on acceleration rates.

The centrifugal forces (at 4,900 rpm) would be acceptable for both materials. Carbon-epoxy is ideal, with its very high strength-to-weight ratio, but needs to have a hard steel rim for wear resistance. Aluminium alloy can take the centrifugal forces, it would resist wear running on PU, but not bare steel.



Steering stability is important, the correct steering geometry would make the pod inherently stable ‘hands-off’, like all road vehicles. Andy Green hand-steered to follow his black line on the salt lake. Automated steering would give the passengers a sway-free ride.

Cheetah will be very stable, with wide curved wheels running in a circular tube. It will not suffer from the hunting which limits railway speeds, a result of the conical rolling surfaces and high centre of gravity over the rails.

The wheels will have very much lower contact pressure and wear than railway wheels. They carry 50% of the weight, have 5 times the contact width and 45% greater diameter. The contact pressure is well within the limits for a hard PU tube liner if used. The wear of the tube can be halved by making the angles of the front and rear wheels slightly different.

Gyroscopic forces are significant, requiring lightweight wheels. The challenge is to bank the pod 45 degrees in 3 seconds when entering a curve. The resulting bearing and axle loads are less than normal cornering forces on a road wheel. The tipping force is small compared to the righting force with the wide-spaced wheels. But the gyro forces impart a skidding force between the wheel and tube, requiring a friction coefficient of about 0.2. This must be considered when designing the wheels and the lead-in to the curves.

Inflatable or solid tyres would overheat quickly, the wheel must be metal-faced. If PU is used to line the tube, it would keep cool as it is only impacted every 30 seconds at the most.

Air bearing skis - the challenges

The air bearing skis are unlikely to work, the flow of air as proposed in Alpha is a fraction of what is required. The compressor inlet would need to be 8 M in diameter. Decades of research has failed with air cushion trains, and this project is infinitely more difficult in a near-vacuum.

Alpha’s estimated airflow for the skis is deficient by a factor of about 30, as can be seen by calculating the air flow leaving the gap between the skis and tube. The pressure ratio is 110 (11 vs 0.1 kPa), so that the flow will be ‘choked’ (if pressure ratio > 2) and at the speed of sound (Kantrowitz again). Alpha’s ski exit flow rate is 11m/s, whereas about 340 m/s is required. These figures are at full speed, flow rate will reduce as the pod slows down and intercepts less air; there is simply not enough air in the tube.

Air bearings work well, but they are machined to micron (0.001 mm) clearances, where the air does form a viscous layer. Very different from a 3 m diameter welded tube with variations of several mm.

Kantrowitz Limit problem caused by air bearing ski outflow.
Alpha relies on the compressor to keep the flow between the pod an tube below the speed of sound. So the Kantrowitz Limit is resolved at the front of the pod. But at the back of the pod, 40% of the air from the first compressor is directed to the air bearing skis, and passes out from the skis into the tube again. So the back of the pod will have a shock wave problem.

The cooling solution

Hyperloop Alpha proposed using water for cooling its motors, compressors etc, as they would quickly overheat in the poor conducting vacuum. The proposal required 290Kg of water over the 35 minute journey. Using the latent heat of vaporisation for water, this water flow would cool 312 Kw of power, which is similar to their figures. But Alpha proposes storing the steam from the boiled water, this is a serious problem. If we boil this water at 100 C, it will produce 9,667 cu M of steam, which is an impossible sized tank. If we boil the water at ambient temperature, the pressure must be lower and the tank needs to be 30 times bigger.

Cheetah uses cooling water like Alpha, but it ejects the steam into the tube, where it is pumped out to condensers. There would be small heat exchangers which evaporates the cooling water at about 20 C, which cool the air for the passengers, water for the electronics, and oil for the mechanical equipment.

The steam after the evaporators is at 4 kPa, and energy is wasted if it is simply ejected into the tube at 0.1 kPa. This energy could be saved by using it for thrust, or driving a turbine to recover part of the 93 kW required to compress the steam into the condensers.

Ice could be used for cooling, but the latent heat of fusion of water is much lower. It would take 1,600 kg of ice to cool 250 kW for 35 mins. But that ice would require over 400 Kw to make, pump and transport, more than doubling the overall energy cost.

Latent heats for steam and ice	
Vaporisation of water	2260 kJ/Kg
Fusion of water (ice)	334 kJ/Kg

Steam

Steam has amazing heat transfer properties, which is why it has always been used for power generation for centuries. What you see coming from the kettle is condensed water droplets, but there is also invisible steam (water vapour) which contains a lot of heat.

A 'Natural Steam Vacuum' is the vacuum formed when a steam-filled container cools to ambient temperature, this is a popular way of preserving fruit and crushing cans. This pressure is about 4 kPa (equivalent to 95,000 ft altitude), if Hyperloop operated at 900 km/h we could run economically and let the dumped steam condense naturally with virtually no pumping cost.

But we want to run at 1,200 km/h, and the friction would be too high. So we reduce the tube pressure to 0.1 kPa, 100 Pa. This means that the steam ejected by the pods needs to be pumped from 0.1 kPa to the condensers at 4 kPa, this consumes 50% less power than pumping to 101 kPa, atmospheric pressure.

There would be a compressor every 10 km along the tube, using about 65 kW at full capacity, pumping the ejected steam into a small cooling-tower condenser. The same compressor would be part of the vacuum-pumping system for evacuating the tube at start-up.

Air in the tube is a problem, as it needs to be pumped out to full atmospheric pressure. All the potential leaks need to be sealed with water, and the airlocks flushed with steam or water. For instance, there will be manhole exits every few km, the seals need to be covered with water. The loss of the water would indicate that there is a leak, and the cost of pumping out the water vapour is lower than air.

Continuous traction will reduce the trip times.

Cheetah uses the wheels for traction, regenerative braking and steering for positioning in the tube. The traction is available along the full length of the tube.

Alpha uses short lengths of linear motors, to give 1g acceleration or braking. There are just 6 places on the whole route where the speed can be changed, a severe restriction imposed by the considerable cost of the linear motors.

Alpha's linear motors give 1g acceleration up to full speed, this is to reduce the length of the motors. But this requires a massive 29,400 kW of power, to be supplied by battery banks at the linear motors. Cheetah's motors cannot be that large.

The trip times using a reduced motor power was analysed, and surprisingly it adds just 2 minutes to the LA-SF trip to reduce the maximum acceleration to 0.25g or max 3,500 kW (0.17g at full speed). That time can be made up by being able to accelerate between corners anywhere, so in fact the trip time could be reduced. The limited acceleration is much more acceptable for the passengers.

The calculations show that for a single acceleration, Cheetah takes 174 secs to get to full speed, and travels 32.2 km. Alpha takes only 34 secs to get to full speed, then cruises to finish the same 32.2 km in a total of 113 secs. So the difference is 61 secs, and the route effectively only has a single acceleration/braking profile, so the overall time difference is 122 secs.

The overall performance for the actual LA-SF trip has been analysed, it includes every corner as shown in the Google maps in the Alpha proposal. This large spreadsheet is available.

Cheetah has another speed advantage over Alpha, it will take the curves at 1g horizontal acceleration, with correct banking the passengers will feel a 42% increase in their weight, but no lateral force. Alpha quotes only 0.5g horizontal acceleration, this may be due to limited banking angles due to engagement with the linear motors.

One emergency situation is is a breakdown of one pod. All the pods behind it, possibly up to 50, would be forced to stop and wait for the problem to be resolved. With wheels, it is possible the disabled pod could be pushed by another pod to an exit, or it may need to be recovered. Using wheels, once the obstruction is cleared, all the pods could continue their journey at normal speed. Alpha would be in a serious situation with a large number of pods stranded between linear motors, with only their low-speed wheels to take them to an emergency exit.

Emergency braking

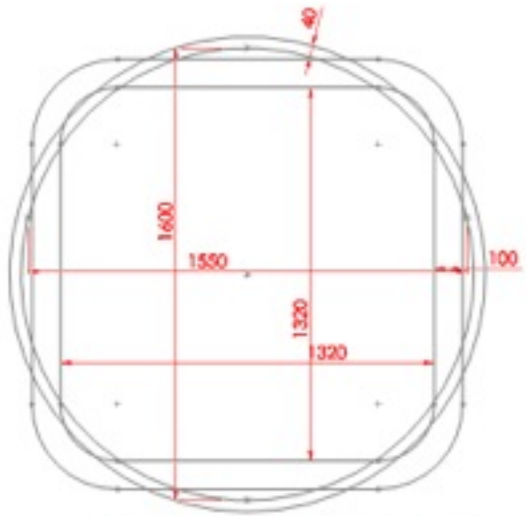
Emergency braking is necessary with at least 1g deceleration required for a 30 second pod spacing. If the tube is bare steel, brake pads could be pushed against the tube wall, they would not overheat because of they are always in contact with the cool steel tube.
If the tube has a PU liner, direct friction pads cannot be used. There could be aerodynamic brakes like an opening umbrella, which are spring-loaded to give the required braking rate.

A tail-mounted parachute should also be fitted as a backup emergency brake.

Round pod vs square section

Cheetah has a round section pressure hull, like all pressurised aircraft. The pressure differential for the Hyperloop pressure hull is 60% greater than aircraft, increasing the structural problems. A square sided hull would require heavy stiffening for the flat sides which takes up a lot of internal space.

The diagram shows two sections which have identical external frontal area, and with the required stiffening to withstand the internal pressure. The round one is 1,550 mm (61") wide (at the shoulders) and 1,600 high, the square one is only 1,320 mm (52") high and wide. The square one would be double the weight and triple the manufacturing cost.



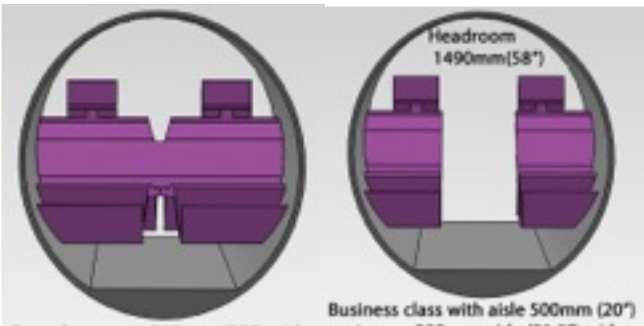
BOTH SECTIONS HAVE THE SAME EXTERNAL FRONTAL AREA

Seating Layouts

The inside diameter of 1.6 M (63") allows 3 seats wide for economy, or 2 seats wide for business class.

An aisle is necessary to allow passengers to move to one of the two emergency exits, or possibly to a toilet during extended delays.

The 2-seats wide gives very wide and comfortable seats, and a usable aisle when the armrests are folded.



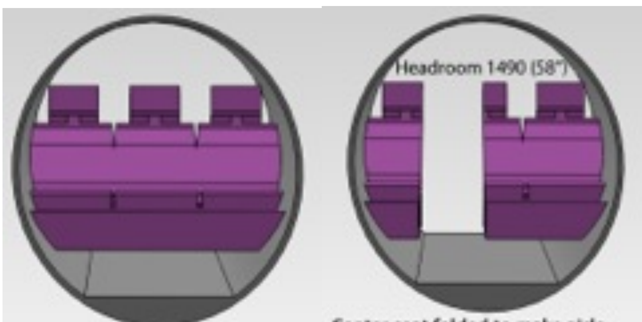
Bus. class seats 700mm (27") wide

Business class with aisle 500mm (20") seats now 550mm wide (21.5") wide

The 3-seats wide layout gives a generous seat width of 20" wide, better than airline economy seats of 17" to 18" wide.

The centre seat can be folded to allow an aisle, but this is tight and only suitable in emergencies.

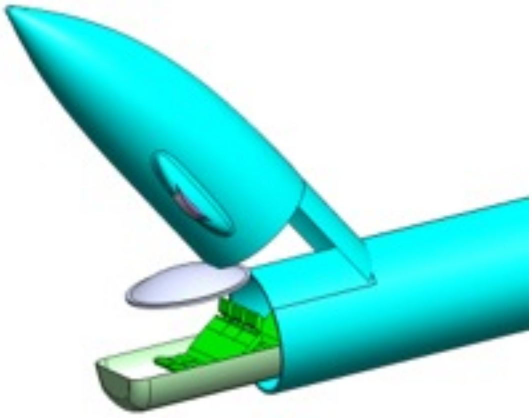
If a permanent aisle is necessary, the layout would be 2-seats wide, and the passengers will be much more comfortable. But the pod would need to be lengthened to get the required capacity.



3 Economy seats 500mm (20") wide

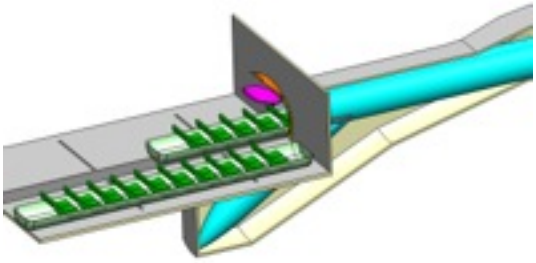
Center seat folded to make aisle, Seats and aisle 400mm (15.5") wide

End door for the airlock



Cheetah has an airlock door on the front, which is accessed by hinging up the front of the pod. This door engages with the airlock door at the station, giving minimum vacuum loss during docking.

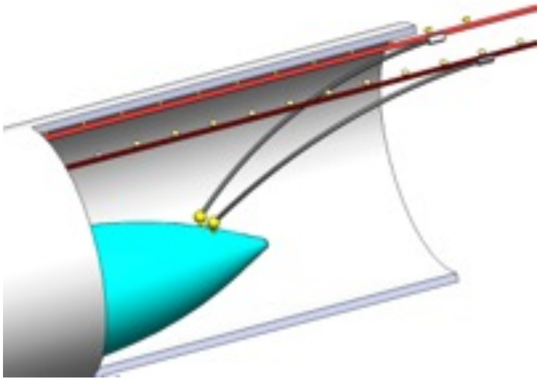
This short video shows the animation of the docking process and passenger module in action. (note the pod front now hinges upwards). The pod engages with the airlock door, so both doors can be opened. The seating module is rolled out, and replaced by the next one.
http://www.youtube.com/watch?v=pWmZVTp5EqU&feature=youtu.be



The turnaround time for the pod is very fast, and the passengers have time to get comfortable in the seating module. The modules can easily be changed to allow for different mixes of economy, business and cargo.

Alpha described side-opening gull-wing doors. With the 10 tons/sq M internal pressure, these would be impractical, and waste a lot of internal space, airliner doors are massive and very complicated. There would need to be full-size airlocks at the station, with high pumping energy cost.

Power supply from rails or batteries



Alpha uses batteries in the pod for all the power, Cheetah now needs extra power for acceleration as well.

This could come from batteries like Alpha, or powered rails in the tube, and pickups on the rear of the pod. But the pod would still need some batteries to maintain passenger air supply and motor to an emergency exit if the whole system lost power.

External powered rails would be more energy efficient, as there is no charge/discharge losses from the batteries. Regenerative braking power would be consumed by other pods.

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Please contact me with any questions, comments, or if you require the calculations.